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An Investigation into an Alternative Fragment Projector for Insensitive Munitions Qualification

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ABSTRACT

The report describes numerical modelling and experimental testing aimed at producing an explosively formed projectile (EFP) that approximates to a right cylinder (where L/D = 1) with a velocity of about 2.5 km/s for consideration as an alternative to the 12.7 mm steel cubes used in the Fragmat Insensitive Munition test.

A large number of EFP designs were modelled using the PC-DYNA2D computer hydrocode and short listed candidates were fabricated for experimental verification. Multiple flash radiography was used to determine the shape, size and velocity of the projectiles, and the results showed varying degrees of correlation with the predictions. Further refinement of one of the designs using numerical modelling led to the development of a near right cylinder, flat faced projectile travelling at approximately 2.25 km/s. The flight path of these projectiles were shown to be highly directional. Experimental results demonstrated that a cluster of EFP charges separated by a thin layer of foam could be used to produce a multi-fragment projector and our data base suggests that the required velocity of 2.5 km/s could be achieved with a Composition B explosive filling. With a relatively small explosive content (0.84 kg for a 3 projectile device compared to 20.9 kg for Fragmat) and a high hit probability the EFP device offers the opportunity of overcoming the two major shortcomings of the Fragmat test vehicle. This assumes that a projectile of the right cylinder form, is an acceptable alternative to the cubical projectiles generated by Fragmat.

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An Investigation into an Alternative Fragment Projector for Insensitive Munitions Qualification

Executive Summary

Insensitive Munitions (IM) may be defined as weapons that have a low vulnerability to hazard stimuli such as fragment strike during production, storage, transport and operation. The many explosives accidents around the world, some with devastating consequences, have stimulated the demand for more emphasis on IM development and testing. Australia has adopted an IM policy. Three hazard assessment tests are considered important for the Australian environment, they are cook off, sympathetic detonation and bullet/fragment impact.

For munitions to pass the fragment impact test, the reaction must not be more than a violent burn after being subjected to a multiple fragment strike. The current fragment impact test (Fragmat) is time consuming and has severe deployment problems due to the amount of explosive it contains; 20.9 kg of Composition B. The accuracy of the projectiles is very sensitive to the placement of the five detonators that are needed to produce a plane shock wave.

The report describes a numerical modelling and experimental testing investigation aimed at producing an explosively formed projectile (EFP) that approximates a right cylinder with a velocity of about 2.5 km/s for consideration as an alternative to the 12.7 mm steel cubes used in the Fragmat Insensitive Munition test.

A large number of EFP designs were modelled using the PC-DYNA2D computer hydrocode and short listed candidates were fabricated for experimental verification. Multiple flash radiography was used to determine the shape, size and velocity of the projectiles, and the results showed varying degrees of correlation with the predictions.

Further refinement of the short listed design using numerical modelling led to the development of a near right cylinder, flat faced projectile travelling at approximately 2.25 km/s. The flight path of these projectiles were shown to be highly directional and our database suggests that the required velocity of 2.5 km/s would be achieved with a Composition B explosive filling rather than the PE4 used in our tests.

It was successfully demonstrated that a cluster of EFPs separated by a thin layer of foam could be used to produce a multiple fragment projector. The total explosive mass for a 3 fragment projector should be approximately 0.84 kg which is considerably less than the 20.9 kg of Fragmat. Thus the EFP cluster offers the opportunity of overcoming the two major problems with the Fragmat test, that is avoiding the collateral damage problems associated with the large mass of explosive filling and the

poor hit probability while being able to maintain the individual fragment mass and velocity.

Consequently, if a projectile shape that is approximately a right cylinder is acceptable as an alternative to the current cubical projectile it is recommended that the Australian Ordnance Council give consideration to supporting a study into developing a finalised design for an EFP fragment projector device for the munition hazard qualification testing of Australian ordnance.

Thus the outcome from the study into the EFP fragment projector is the potential for providing the ADF and its contractors with cost benefits and clear logistical and deployment benefits compared to the existing Fragmat test for munition hazard qualification.

Contents

1. INTRODUCTION

Insensitive Munitions (IM) may be defined as weapons that have a low vulnerability to hazard stimuli such as fragment strike during production, storage, transport and operation. Many explosives accidents around the world, some with devastating consequences, has stimulated the demand for more emphasis on IM development and testing [1]. Three hazard assessment tests were considered important for the Australian environment, they are cook off, sympathetic detonation and bullet/fragment impact. For the munitions to pass the fragment impact test, the reaction must not be more than a violent burn after being subjected to a multiple fragment strike. The fragments striking the munition in the standard Fragmat impact test are half inch (12.7 mm) steel cubes travelling at an average velocity of 2.5 km/s. This would represent the high portion of the fragment velocity threat spectrum.

The current fragment impact test (Fragmat) [2] is time consuming and has severe deployment problems due to the amount of explosive it contains; 20.9 kg of Composition B. The accuracy of the projectiles is very sensitive to the placement of the five detonators that are needed to produce a plane shock wave.

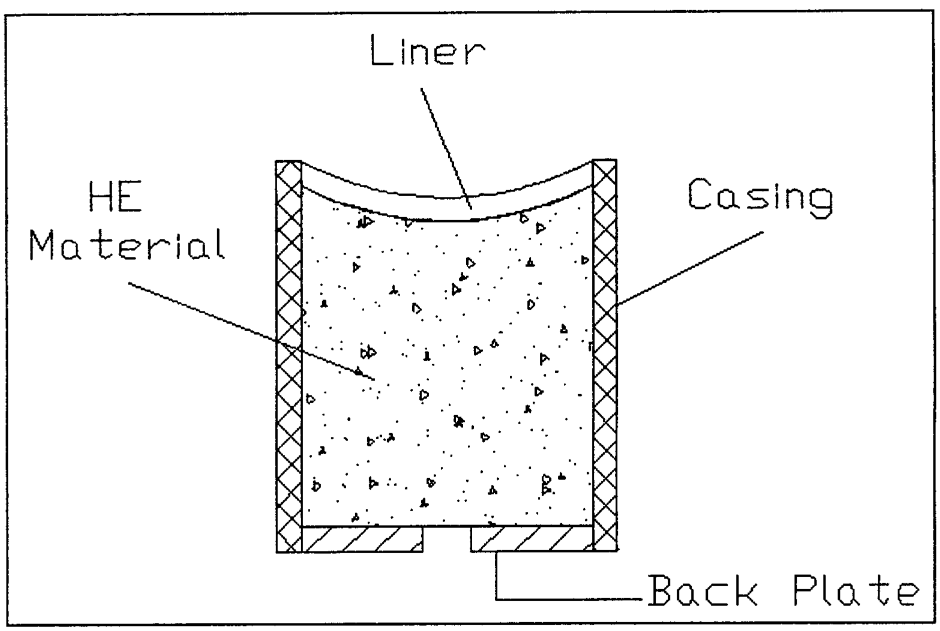

Figure 1. Cross-section of a typical EFP charge.

Explosively Formed Projectiles (EFPs) may offer an alternative, mainly due to their ease of fabrication and deployment, significant reduction in explosive filling and therefore collateral damage, and the projectiles are highly directional. A typical EFP charge, depicted in figure 1, consists of a metal liner (from which the projectile is

formed) confined at one end of an explosive-filled cylindrical tube. A plate is positioned at the back face of the charge to center a small detonator.

This report describes numerical modelling and experimental testing aimed at producing a cluster of approximately right cylindrical EFPs with a velocity of approximately 2.5 km/s as an alternative to the 12.7 mm steel cubes generated by the Fragment device.

2. NUMERICAL COMPUTATIONS

2.1 General Comments

DYNA2D [3] is a Lagrangian and Arbitrary Lagrangian-Eulerian finite element computer code developed at the Lawrence Livermore National Laboratory by Hallquist, 1984. It can be used to model material deformation, shock wave interaction and detonation events in a two dimensional, axisymmetric or plain strain environment. The PC version was developed by Murphy in 1991 and has many advantages over its big brother, in particular it's convenience, cost effectiveness and rapid turn-over of results. It also comes with a built-in library of commonly used material data. It can handle up to 12,000 elements for a 4 M Byte RAM system.

DYNA2D consists of three phrases of file processing, they are the Maze [4], a pre-processor, Dyna, a finite element processor and Orion [5] as a graphics post-processor. Maze is used to generate a data file that describes the model as nodes, elements, boundary lines and materials. The output file from the Maze pre-processor acts as the input field for DYNA2D, which then processes the numerical model. The output from the finite element process, is fed into the Orion post-processor, this enables the results to be viewed in a variety of graphical presentations which are both informative and easily interpreted.

A number of EFP charges were modelled using the DYNA2D hydrodynamic code on an IBM compatible 486-33 MHz personal computer. Various factors all contribute to the simulation time, such as the size of the elements that make up the charge, how long after detonation the projectile is modelled and so forth. Typically, an EFP simulation run would take around an hour or so.

2.2 Modelling Technique

The numerical model was generated using the Maze pre-processor either interactively or in a batch mode (writing a Maze file). The model is described in terms of lines outlining each individual part and parts are formed by specifying lines that created a closed shape. The parts that mattered the least are coarsely meshed while the parts of interest or critical to the results are more finely grided. It may be necessary to merge two parts together in situations where complex shapes are involved.

Slidelines are needed to describe the interaction between two adjoining parts. There is a number of slidelines to choose from, so it is important that the correct one is selected. The slidelines used in the simulation were the type 3, frictionless sliding with voids which enables the parts to separate, and the type 0, stonewall. It is also important to specify all necessary slidelines, if this is not done correctly the simulation will be invalid. In the third phase of Maze, the materials were specified and changes to the material properties defined.

Occasionally, it is necessary to run the DYNA finite element processor twice [6]; first to determine the time of maximum projectile velocity. At this time, during the second run, the explosive, side casing, locator and slidelines can be deleted as they have minimum effect on the formation of the projectile. Some of the liner's edge elements which suffer severe deformation can be deleted. The rezoning operation leaves only the projectile, which generally did not have largely distorted elements, and so the computer was able to simulate its changing shape more quickly saving valuable computer time.

Once DYNA2D had finished processing, the results were viewed with the Orion post-processor. The velocity vectors were plotted, to check that the required speed had been reached and that the shape was in equilibrium. The projectile cross-section was plotted to determine if the shape of the projectile was satisfactory. The projectile cross-section was assessed against the set of EFP parameters under study.

2.3 The Refined EFP Model

During the course of modelling, a large range of EFP governing parameters were studied. They included (a) liner material and radius of curvature, segmented liners, linear and contoured liner thickness, (b) confinement material and thickness, (c) explosive charge length and diameter, (d) weights added on the liner to shear off unwanted mass. Four designs were nominated for fabrication and experimental verification, and the refined EFP design was the final product of this study.

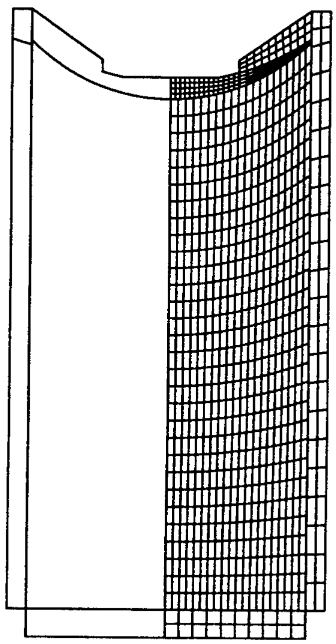

Figure 2. The refined EFP charge for the fragment impact test.

The refined EFP charge, illustrated in figure 2, comprises a steel cylinder, perspex plate for positioning the detonator at the base, steel liner and was filled with Composition C-4 explosive (PE-4 bearing close similarity with C-4 was substituted in the fabricated devices). The left hand half side of figure 2 shows the outline of the charge while the mirror half is the griding up of the EFP model for the numerical analysis. The liner, being the part of interest, was more closely meshed with 126 elements and the explosive filling had 20 x 30 elements. Coarser grids were used for less significant components such as the casing and back locator. Using the modelling technique described earlier, it was found that the explosive-liner interaction reached the maximum velocity around 30 μs after detonation. At this point the casing, back-locator and high explosive were deleted from the model as they no longer influenced the EFP formation process. To save computation time the outer ring added to the liner was also deleted. This was performed with the rezoning facility during the DYNA computations. Tabulated in table 1 are the material models used in the simulation of the refined EFP design.

Table 1. Material models used in the EFP charge computation

Component	Material Model	*EOS
Steel Liner, 4340	Johnson-Cook [7]	Grüneisen
C-4 Explosive	Linear Burn	JWL
Perspex Back-Locator	Steinberg-Guinan	Grüneisen
Steel Case, 1006	Johnson-Cook	Grüneisen

* Equation of State

3. EXPERIMENTAL

3.1 Test Configuration

The refined EFP charge is used as an example of our set-up and procedure and is illustrated in figure 2. It consists of three main components. The perspex locator for centralising the detonator, a mild steel cylindrical confinement tube, 105 mm long and 50 mm diameter with a wall thickness of 3.45 mm, and a variable thickness liner 50 mm in diameter manufactured from Vibrac (EN25) steel.

The liner was adhered to the charge case using Loctite and once set, was hand filled with plastic explosive (PE 4). Typically the EFP devices contained between 0.2 and 0.3 kg of explosive. When prepared for firing the charge was supported on a thin walled PVC tube over a witness block. The PVC tube allows for the nominal standoff for the EFP formation from the liner and measurements of the flight characteristics in free air with flash radiography prior to impact on the witness block. A reference point is also included in the set up for the flash radiography measurement of the projectile position and velocity.

For the multiple firings, three individual charges were secured together. A 20 mm thick polystyrene divider was placed between each charge to create a triangular formation. This configuration was also supported upon a thin walled PVC tube, with a standoff length of 500 mm from the witness block.

Each charge was fired simultaneously from an EBW detonator. The four flash radiographs were taken during the range of 125 to 185 μs from the EBW firing.

3.2 Instrumentation

Projectile velocities were measured using multiple flash radiography techniques (FXR). These experiments were carried out with a four channel FXR system. Two orthogonal 300 kV and two orthogonal 600 kV pulsers were arranged around the common central fragment axis-of-flight.

The FXR pulsers were triggered from the Exploding Bridgewire (EBW) detonator. A delay was set into the system to trigger the pulsers at the times based on the modelling prediction, hence the estimated position of the projectile at various distances can be confirmed with experiments. Images were recorded by a film and the florescent intensifying screen combination placed in a protective cassette and positioned near the charge. Projectile velocities were calculated from the radiographic images and recorded times.

4. RESULTS AND DISCUSSION

4.1 Comments on Numerical Prediction for Different Types of EFPs

The DYNA finite element code was used to evaluate a large number of EFP charge designs. They included variation to;

a) liner geometry and material,
b) confinement thickness and material,
c) charge diameter and length, and
d) added weight or outer ring on the liner to shear off unwanted projectile mass.

However they can be categorised into four distinct design types; linear liner, segmented liner, contoured liner and contoured liner with a ring. Of these designs, only the contoured liner with the added ring was able to come close to the desired projectile shape and velocity required for the Fragmat test.

Linear Liner The initial designs involved a typical EFP liner (see figure 1) where the thickness of the liner is constant. Figure 3 shows this projectile in flight, where it can be seen not to meet the required characteristics of this test. The projectile's outer perimeter having a preference to fold back and had a relatively thin nose thickness, which will quickly erode away.

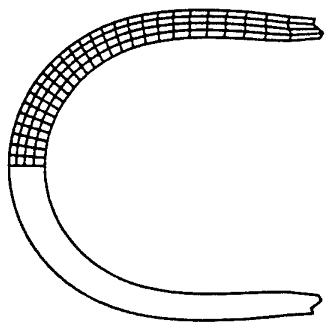

Figure 3. A typical steel EFP formed from a constant thickness liner.

One of the major problems that was encountered when attempting to form the required shape from a linear liner, was that the mass of the material could not be concentrated towards the centre line of the projectile. Parameters that were investigated to see if the front of the projectile would 'bulk up' were :- varying the linear liner thicknesses, changing the radius of curvature of the liner, varying the charge diameter and changing the liner material. None of these methods were successful or even looked promising. However, the results did suggest that liners with a variable thickness may contribute to overcoming the problem.

Contoured Liner The thickness of a contoured liner gradually increases or decreases as it moves away of the apex. In this instance, the contoured liner has a smaller edge thickness than the apex thickness. The mass differential between the edge and the center of the liner would enable material flow to form a mass concentration behind the nose of the projectile.

As expected the contoured liner EFP (figure 4) exhibited an improved profile compared to the linear liner EFP's. The projectile has edges which are thinner than the apex while still having good velocities. It was possible to get the leading edge to be almost flat with a satisfactory velocity, but unfortunately in these instances the edges of the liner did not fold back behind the body of the projectile.

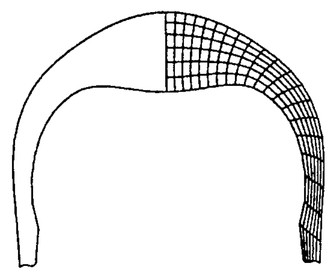

Figure 4. An EFP profile of a steel contoured liner.

Numerical results also suggest that the harder less ductile steel, ie. 4340, is more suitable for this application than the softer more ductile steel, ie. 1006, which tends to produce fragments with a more rounded front. The problem encountered with the variable thickness liner EFP's was that they were too wide and the leading face thickness was not uniform or thick enough. As the required thickness is about 12 mm a method is required to get the shape to thicken through the apex and also become thinner about its axis of symmetry.

Contoured Liners with a Ring In order to reduce the width of the projectile a method to shear off the outer edges of the projectile was investigated. To do this an outer ring was machined round the edge of the liner. The proposal was that the added weight around the edge of the liner would slow the edge down and shear off the unwanted material from the outer part of the EFP.

The effect of the added ring on the EFP is shown in figures 5a and 5b. Notice that the EFPs are a similar shape except the one on the right has the wing sheared off during the formation of the projectile.

Figure 5(a). Profile of the EFP from a contoured liner. 5(b) Profile of the EFP from a contoured liner with a ring (right).

To remove more material from the EFP, it is necessary to cover more liner surface area by decreasing the hole diameter of the ring, so that only the middle portion of the liner is left uncovered. On detonation, this fast moving centre portion will shear off from the rest of the liner to form a fragment.

Segmented Liner A segmented liner is either a variable or a linear liner that has had a centre segment removed and then glued back into place. The cut allows the centre piece of the liner to be subjected to a larger amount of pressure because the explosive charge diameter is larger than this segment. The outer segment of the liner creates a frictional force on the inner segment of the liner, therefore stretching the centre as it is projected forward by the explosive.

Initially the segmented liner chosen was a variable liner. It was soon realised that if the edges were thinner than the apex thickness then they would travel at a higher speed and interfere with the critical centre liner segment. To over come the problem the edges were gradually made thicker, until the result was a linear segmented liner.

The fragment produced from the linear segmented liner, had a reasonably flat front edge with a good mass concentration close to the nose of the projectile. The size and shape approached that of a right cylinder and the velocity of 2.29 km/s was reasonable at 200 μs after detonation.

4.2 Experimental Validation of Numerical Predictions for Shortlisted Candidate EFPs

Based on the above work only four candidates were nominated for fabrication for experimental validation. Figures 6 to 9 shows the comparison between the predicted fragment profile (left) and the actual projectile shape (right).

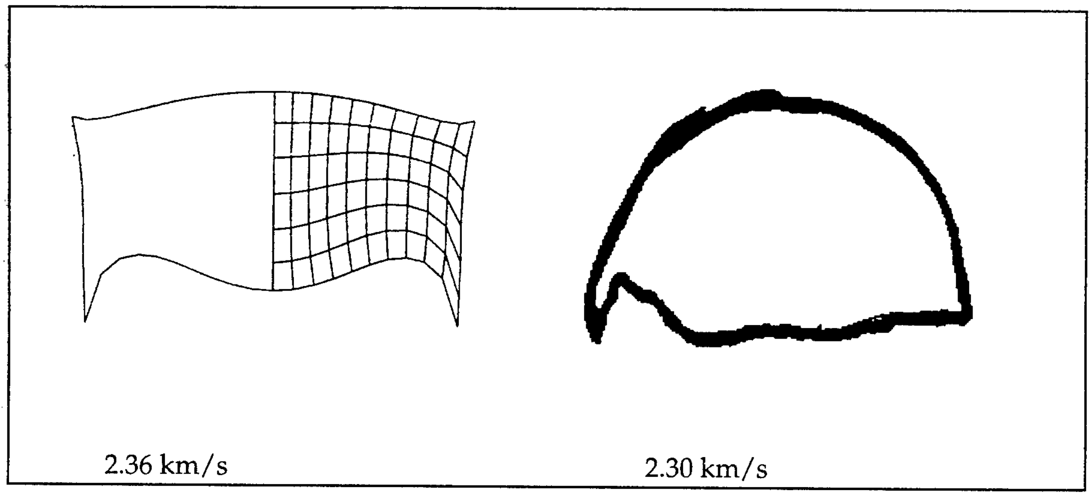

Figure 6. A fragment profile of steel contoured liner (first candidate).

The size of the actual fragment in figure 6 (from a contoured Liner) captured on the negative film was approximately 15 mm wide by 10 mm in thickness. The diameter and thickness show good correlation with that predicted by the computer simulation. The leading edge of the fragment obtained experimentally is quite different to that

predicted; the predicted edge is more flat while in reality it is hemispherical. The experimental velocity is consistent with that predicted by the code.

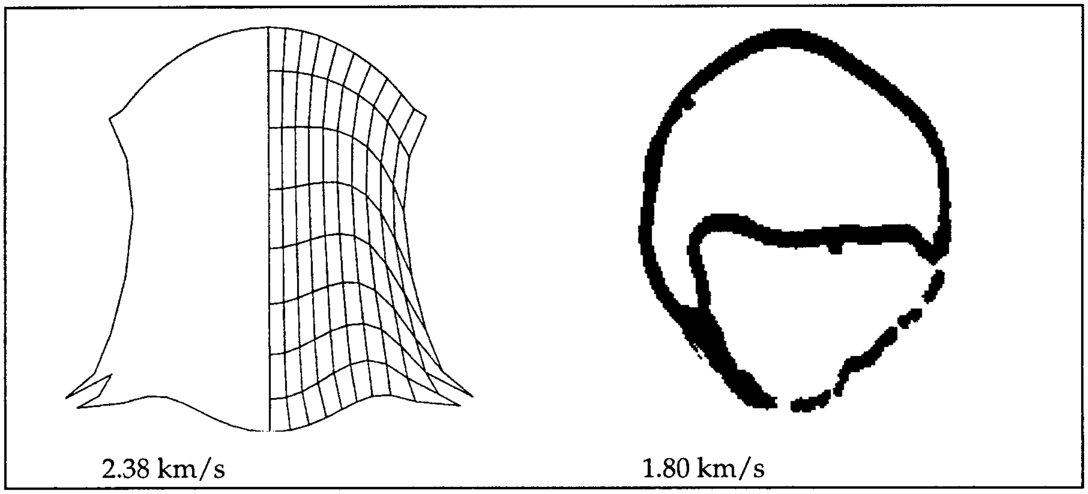

Figure 7. A fragment profile of a soft steel contoured liner (second candidate).

The contoured liner candidate in figure 7 shows that the predicted projectile shape was different to that produced experimentally. Again the actual diameter of the fragment, 10 mm, shows good correlation with that predicted. The length of the fragment is actually quite different as the rear half of the fragment is hollow. The length excluding the hollow section is only 7 mm. The velocity deviated a long way from the computational prediction by 24%.

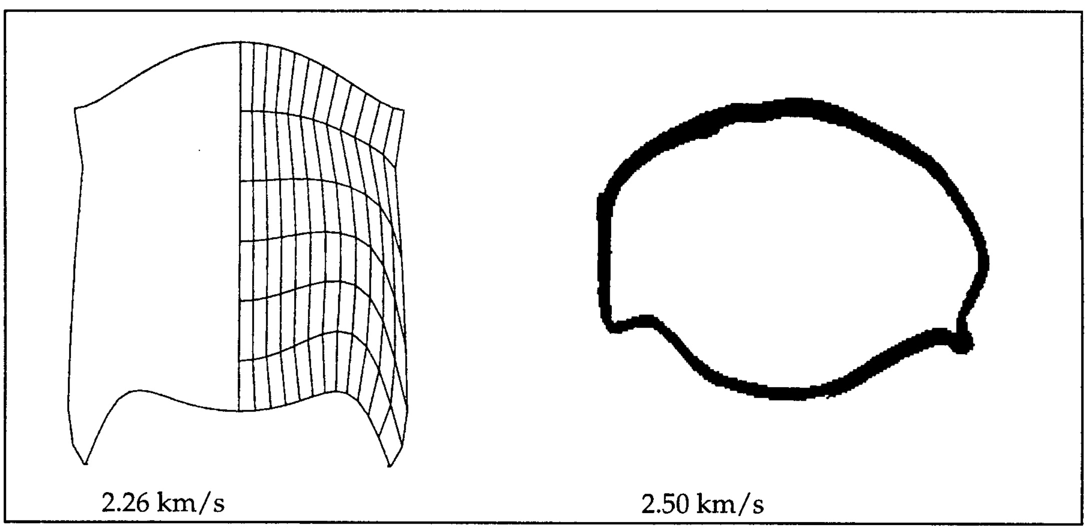

Figure 8. A fragment profile from a contoured liner (third candidate).

The contoured liner candidate in Figure 8 gives an illustration of the fragment that is the closest of the four candidates to the shape required. The predicted fragment diameter and the leading edge compares well with the experimental result. However, the length of the fragment is not as great as that predicted. This projectile was captured and its dimensions checked with those measured from the flash radiographs. The actual fragment measured approximately 10 mm thick by 14 mm in diameter. The predicted velocity compares well with the measured velocity which is very close to that required. This design was short listed for further refinement as described below in Section 4.3.

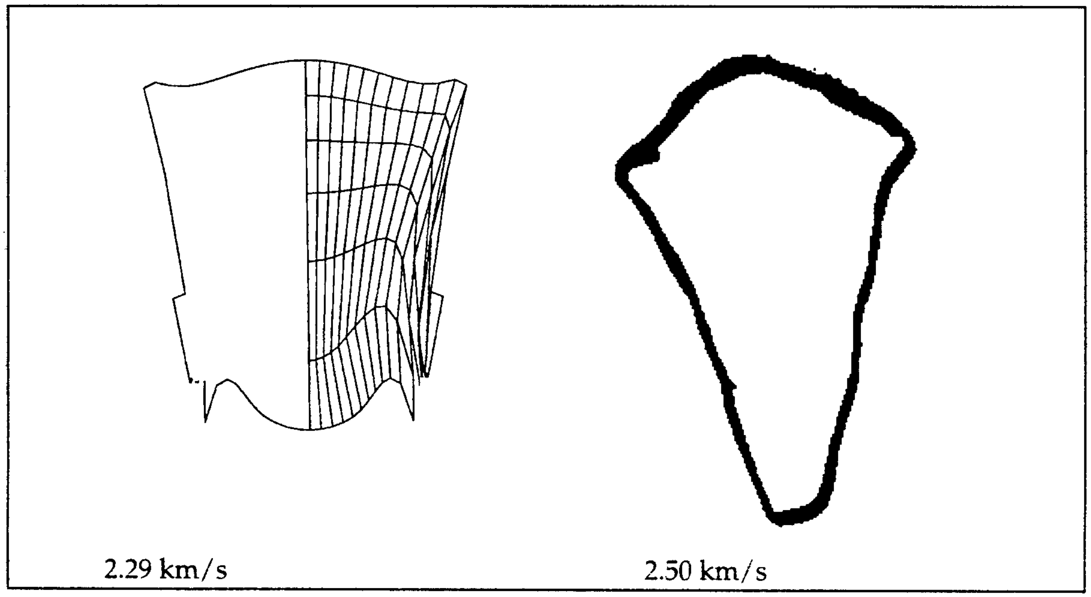

Figure 9. A fragment from a segmented liner (fourth candidate).

The segmented liner candidate (figure 9) shows that the profile of the fragment is close to that predicted and that its velocity is approximately that required to simulate the Fragmat system. The FXR image shows a projectile size about 16 mm diameter and narrowing down as it approaches the 18 mm length. The leading edge of the fragment would need to be flatter and the tail section thickened if this model is to be used as a Fragmat particle. Thus this candidate device was rejected since it was anticipated that considerably more effort would be needed in both modelling and experimentation to undertake these design changes.

With all of these designs it would be necessary to prevent the retraining ring or outer segment from impacting the ordnance under test. In order to screen out the unwanted material the fragment could be fired through a shield, with a hole in it, situated in front of the EFP.

4.3 The Refined EFP Charge with Experimental Verification

The result of the four nominated EFP charges suggest that further design refinement was necessary to improve the shape of the fragment from the short listed design.

Based on the contoured liner with a ring model, a number of designs were modelled and fine tuned. After many simulations, a fragment approximating the ideal shape was achieved. Figure 10 shows the comparison between the numerical prediction (left) and radiography image tracing (right) of the projectile and the result is the closest to the projectile characteristics used in the Fragmat IM test produced by the investigation.

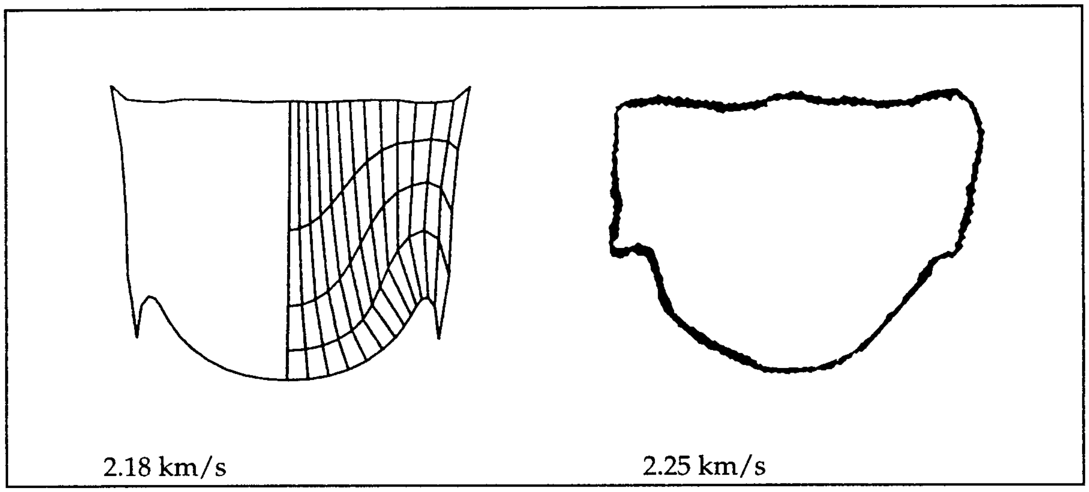

Figure 10. The fragment from the refined EFP charge.

The predicted shape and size of the fragment agree exceptionally well with the adjacent flash radiography tracing. The actual fragment produced from the refined EFP design had a reasonably flat front and the size was measured at 14 mm diameter by 11 mm in thickness. The back face of the fragment is bulged and this is a deviation from the Fragmat projectile but the front impact face is reasonably plane and this is an important characteristic for the IM test. The velocity is at the lower limit for meeting the IM test velocity requirement, the code under estimated the actual velocity (2.25 km/s) by about 3%. Overall, the predictions correlate well with the experimental results. It was concluded that a reasonable match had been achieved between the characterisation of the explosively formed projectile and those generated by the Fragmat device, albeit the former approximates a right cylinder projectile while the latter is a cube. The explosive mass of the EFP was 0.28 kg.

4.4 Multiple Fragment Projector

Having successfully demonstrated that it was possible to produce a suitable single fragment from an EFP type device it was also necessary to prove the multi-fragment capability for this EFP approach.

Three refined EFP charges were tied together in a triangular fashion separated by thin foam. This buffer zone allows the charge to expand, upon detonation, until the fragment is sheared off from the remaining projectile. Hence the directional flight path of the fragments can be maintained. The total explosive filling mass of the three EFPs was about 0.84 kg.

It was not possible to use DYNA2D to model this particular situation because the hydrocode is an axisymmetric code, nevertheless, DYNA2D was employed to investigate the size of the buffer zone. The charge deformation distance was selected by estimating the radial expansion of the EFP charge can at the time that the fragment detaches from the rest of the projectile.

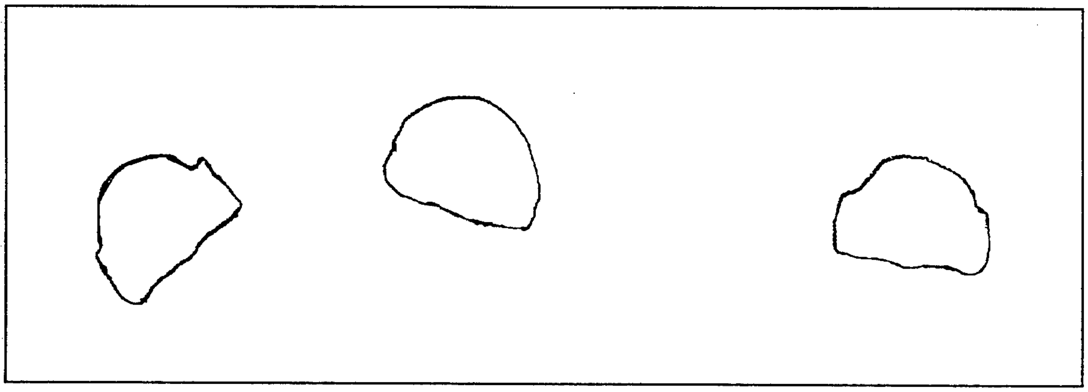

Figure 11. Fragments from three refined EFP charges.

Illustrated in figure 11 is the fragments resulting from strapping three refined EFP charges together. The shape and size compares well with the numerical result and the velocity tends to be slightly less than that predicted. However, our data base suggests that a Composition B explosive filling would be expected to produce the correct projectile velocity. The profile of the three fragments show very similar characteristics in size and velocity. The size of the three fragments as measured on the FXR image were about 14 mm diameter by the 11 mm in thickness. The velocity of the fragments was calculated to be around 2.2 km/s. Figure 11 also shows that the flight path of the three fragments was highly directional, hence proving that the small separation zone was adequate to avoid charge expansion interference. However two of the three projectiles did show signs of tumbling, this may be unavoidable considering the fragment's crude aerodynamic profile that needs to travel through the atmosphere at great velocity. Indeed similar observations have been made on the tumbling motion of the cubes in the Fragmat test.

5. CONCLUSION

DYNA2D was successful in the rapid screening of EFP charge configurations while designing novel projectiles for the purpose of fragment impact studies.

The modelling enabled various EFP governing parameters to be investigated such as linear geometry, confinement effect, and radius of curvature. Numerous designs were modelled using the combinations of these governing factors. Four short listed EFP designs were evaluated experimentally. The flash radiography images of the fragments showed various degrees of correlation with the predictions and three were assessed as unsuitable for further consideration as an alternative IM test projectile.

Further design refinement and fine tuning of the short listed candidate led to the development of a more suitable projectile as an IM test alternative. The projectile produced was highly directional and had a reasonably flat front face for impacting ordnance. The size of the fragment was measured to be approximately 14 mm in diameter by 11 mm thick. The velocity, 2.25 km/s, was slightly less than required but this is expected to be overcome by the use of a Composition B explosive filling.
The explosive mass of the single EFP device was 0.28 kg.

It was successfully demonstrated that a cluster of EFP's separated by a thin layer of foam could be used to produce a multiple fragment projector. The total explosive mass for a 3 fragment projector would be approximately 0.84 kg which is considerably less than the 20.9 kg of Fragmat. Thus if a projectile approximately a right cylinder is accepted as an alternative to the cubical projectile then the EFP device has the potential of offering clear logistical and deployment benefits compared to the existing Fragmat test vehicle.

It is recommended that the Australian Ordnance Council give consideration to supporting a study into developing a finalised design for an EFP fragment projector device for the hazard qualification testing of Australian ordnance.

6. ACKNOWLEDGMENTS

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19. ABSTRACT

The report describes numerical modelling and experimental testing aimed at producing an explosively formed projectile (EFP) that approximates to a right cylinder (where L/D = 1) with a velocity of about 2.5 km/s for consideration as an alternative to the 12.7 mm steel cubes used in the Fragmat Insensitive Munition test.

A large number of EFP designs were modelled using the PC-DYNA2D computer hydrocode and short listed candidates were fabricated for experimental verification. Multiple flash radiography was used to determine the shape, size and velocity of the projectiles, and the results showed varying degrees of correlation with the predictions. Further refinement of one of the designs using numerical modelling led to the development of a near right cylinder, flat faced projectile travelling at approximately 2.25 km/s. The flight path of these projectiles were shown to be highly directional. Experimental results demonstrated that a cluster of EFP charges separated by a thin layer of foam could be used to produce a multi-fragment projector and our data base suggests that the required velocity of 2.5 km/s could be achieved with a Composition B explosive filling. With a relatively small explosive content (0.84 kg for a 3 projectile device compared to 20.9 kg for Fragmat) and a high hit probability the EFP device offers the opportunity of overcoming the two major shortcomings of the Fragmat test vehicle. This assumes that a projectile of the right cylinder form, is an acceptable alternative to the cubical projectiles generated by Fragmat.

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